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All-Optical AND Gate using Optical Hard Limiter with QD-SOA based on Self-Phase Modulation

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Abstract—We propose an all-optical AND gate using an optical hard limiter (OHL). The OHL is based on the Mach-Zehnder interferometer (MZI) with quantum-dot semiconductor optical amplifiers (QD-SOAs). The proposed operation utilizes self-phase modulation (SPM), which is one of several nonlinear optical phenomena in QD-SOA. We determine the output signal waveform and extinction ratio (ER) by numerical analysis. Additionally, we show that the proposed AND gate is capable of operation at 840 Gbit/s.

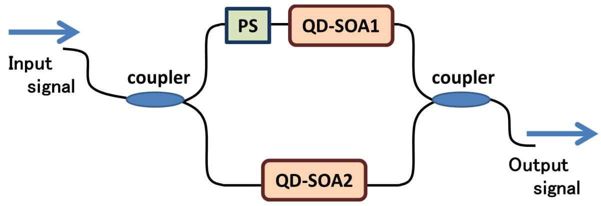

Fig. 1: Configuration of OHL

1. Introduction

All-optical signal transmission, which uses high-speed processing to overcome the speed limit of electro-optic conversion, is expected in next-generation ultrafast networks. In particular, all-optical logic gates are key elements in all-optical networks, such as those for binary signal processing [1]. The AND gate is one of the common and basic logic operations.

Recently, several all-optical AND gates have been reported [1], [2]. In particular, an quantum dot semiconductor optical amplifier (QD-SOA) is an optical device that enables high material gain and ultrafast response [2], [3]. For example, an all-optical AND gate using an InAs QD-SOA and a ring resonator has been demonstrated at up to 160 Gbit/s [2]. The QD-SOA uses several novel nonlinear optical phenomena of all-optical signal processing. In particular, the technique based on self-phase modulation (SPM) is one of the simplest ways to provide QD-SOA functionality [4].

In this paper, we propose an all-optical AND gate using an optical hard limiter (OHL) with a QD-SOA based on SPM. Operation is demonstrated with 840 Gbit/s return-to-zero (RZ) Gaussian signals by numerical analysis using the transfer matrix method (TMM). In Section 2, we present the OHL model. In Section 3, we describe the configuration, operation principle and theoretical model for the proposed AND gate. The numerical results are presented in Section 4. Finally, the conclusions of this study are addressed in Section 5.

2. Optical Hard Limiter Model

A schematic diagram of the OHL used in this paper is shown in Fig. 1 [5]. The OHL, based on the Mach-Zehnder interferometer (MZI), consists of a phase shifter (PS), two QD-SOAs and two 3-dB couplers. The input signal is split by the first coupler and diverges into different signals. The signal in the upper arm propagates through the PS and QD-SOA. However, the signal in the lower arm only propagates through the QD-SOA. Finally, the two signals are coupled by the second coupler and generate an output signal.

SPM, one of the nonlinear phenomena in a QD-SOA, can cause a variation in the refractive index of the medium. This variation in refractive index causes a phase shift in the light. The linewidth enhancement factor of the QD-SOA and signal intensity influence phase shift value. In Fig. 1, two QD-SOAs in the OHL have different linewidth enhancement factors. Hence, the amount of the phase shift by SPM is different between the upper and lower arms in the MZI.

The amount of the phase shift changes according to the input signal intensity. When the intensity of the input signal of the OHL is low, the signal through the two arms acquires a phase difference of π by SPM and PS. Therefore, at the second coupler, the input signal interferes destructively and the output signal is low. On the other hand, when the intensity of the input signal is high, the signal propagating through the arms does not acquire a phase difference of π. Hence, the intensity of the output signal is high due to constructive interference, and so we can control the output signal by the input signal intensity. This principle is the same as the operating characteristics of the OHL.

3. All-Optical AND Gate based on OHL

A schematic diagram of the proposed all-optical AND gate is shown in Fig. 2. It consists of a power combiner and an OHL. The output signal from the power combiner is fed into the OHL. The two input signals to the power

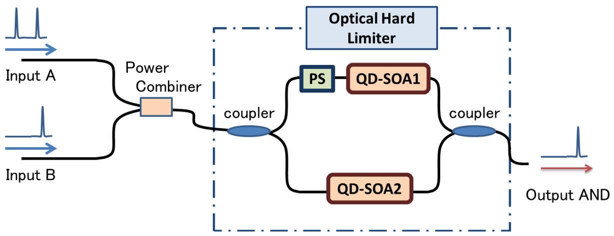

Fig. 2: Configuration of proposed all-optical AND gate

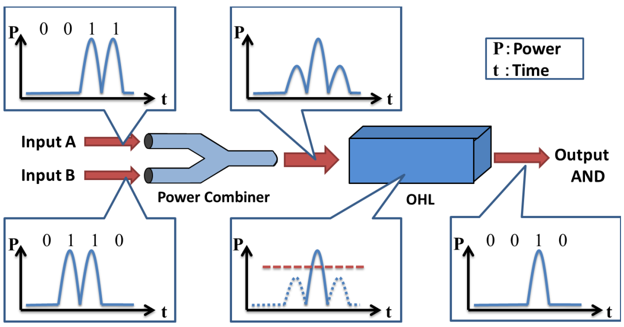

Fig. 3: Concept of proposed all-optical AND gate

combiner and the output signal from the OHL are the input and output of the AND gate.

3.1. Operation Concept

Fig. 3 depicts the operation concept of the AND gate. "0" or "1" in the figure express the logical states determined by the light intensity. The behavior in Fig. 3 agrees with the values in Table 1, which is the truth table for the AND operation. When $(A, B) = (1, 1)$, the output signal from the power combiner exceeds the threshold of the OHL, and hence the output becomes "1". In contrast, when $(A, B) = (0, 0), (0, 1)$ or $(1, 0)$, the output signal from the power combiner does not exceed the threshold of the OHL, and hence the output becomes "0". Based on this concept, an AND gate can be realized: the two input signals to the power combiner and the output signal of the OHL correspond to the input and output of AND gate, respectively.

3.2. Theoretical Model

In this section, we formulate a theoretical model for the proposed all-optical AND gate using an OHL. We use the TMM for the numerical analysis. We assume that the QD-SOA is divided into small sections of the same length. We also assume that the carrier density, gain, and phase shift are uniform in each section [6].

The output power of the OHL, P_{OHL}, is given by [5]:

$$P_{\mathrm{OHL}} = \frac{P_{\mathrm{in}}}{4}\left\{G_1 + G_2 + 2\sqrt{G_1 G_2}\cos\left(\Delta\phi + \phi_1 - \phi_2\right)\right\} \quad (1)$$

where P_{in} is the input signal power, G_1 and G_2 are the total gains of the QD-SOA1 and the QD-SOA2, respectively.

Table 1: Truth table of AND operation

Input A	Input B	Output AND
0	0	0
1	0	0
0	1	0
1	1	1

The phase shifts for the signals propagating through QD-SOA1 and QD-SOA2 are ϕ_1 and ϕ_2, respectively. $\Delta\phi$ is the value of the phase shift in the PS. We set $G_1 = G_2$ because the two QD-SOAs in the OHL have the same parameters except for the linewidth enhancement factor that influences the phase shift. From Eq.(1), we confirm $P_{\mathrm{OHL}} = 0$ when the cosine value, which is the phase difference between the two arms in the MZI, acquires π. The equations for the gain and phase shift, G and ϕ, in the QD-SOA are given by:

$$G = \exp\left\{\sum_{i=1}^{N}\left(g_{\max}\left(2f_i - 1\right) - \alpha\right)\times\left(\frac{L}{N}\right)\right\} \quad (2)$$

$$\phi = -0.5\times\alpha_H \sum_{i=1}^{N} g_{\max}\left(2f_i - 1\right)\times\left(\frac{L}{N}\right) \quad (3)$$

where $g_{\max}$ is the maximum model gain, α is the loss coefficient, α_H is the linewidth enhancement factor, L is the length of the QD-SOA, N is the number of divisions in the QD-SOA used for numerical analysis of the performance, and f_i is the ground state (GS) carrier occupation probability at the $i - th$ section of the QD-SOA.

The QD-SOA is assumed to have two energy states, GS and excited state (ES), and is accompanied by a two-dimensional wetting layer (WL). The rate equations for the WL, ES, and GS are given by:

$$\frac{\partial N_w}{\partial t} = \frac{I}{qV} - \frac{N_w(1-h)}{\tau_{w2}} + \frac{\hat{N}_Q h}{\tau_{2w}} - \frac{N_w}{\tau_{wR}} \quad (4)$$

$$\frac{\partial \hat{N}_Q h}{\partial t} = \frac{N_w(1-h)}{\tau_{w2}} - \frac{\hat{N}_Q h}{\tau_{2w}} - \frac{\hat{N}_Q h(1-f)}{\tau_{21}} + \frac{\hat{N}_Q f(1-h)}{\tau_{12}} \quad (5)$$

$$\frac{\partial \hat{N}_Q f}{\partial t} = \frac{\hat{N}_Q h(1-f)}{\tau_{21}} - \frac{\hat{N}_Q f(1-h)}{\tau_{12}} - \frac{\hat{N}_Q^2 f^2}{\tau_{1R}} - \frac{g}{L_w W E_n} P \quad (6)$$

where N_w is the electron density in the WL, h and f are the electron population probabilities for ES and GS, respectively, t is the time, E_n is the photon energy, P is the optical power, q is the quantum of electricity, V is the active layer volume given by $V = L \times L_w \times W$, $\hat{N}_Q$ is the density of QDs given by $\hat{N}_Q = N_Q / L_w$, and g is the model gain given by $g = g_{\max}(2f - 1)$. The other device parameters used are summarized in Table 2.

The power of the output signal from the power combiner, P_{PC}, with the same wavelength of the input signals is given by:

$$P_{\mathrm{PC}} = \frac{1}{2}\left(P_{\mathrm{A}} + P_{\mathrm{B}} + 2\sqrt{P_{\mathrm{A}} P_{\mathrm{B}}}\right) \quad (7)$$

Table 2: Parameter values used for QD-SOA [5]

Symbol	Description	Value	Unit
L	Effective length of the active layer	2×10^{-3}	m
L_W	Effective thickness	0.2×10^{-6}	m
W	Effective width	2×10^{-6}	m
N_Q	Surface density of QDs	5×10^{14}	m^{-2}
v_g	Group velocity	7.856×10^{7}	m/s
a	Waveguide loss	300	m^{-1}
$g_{\max}$	Maximum module gain	3000	m^{-1}
a_{H1}	Linewidth enhancement factor (QD-SOA1)	1	-
a_{H2}	Linewidth enhancement factor (QD-SOA2)	0.1	-
τ_{w2}	Carrier relaxation time (WL to ES)	3×10^{-12}	s
τ_{2w}	Carrier escape time (ES to WL)	1×10^{-9}	s
τ_{wR}	Spontaneous radiative lifetime in WL	2×10^{-9}	s
τ_{21}	Carrier relaxation time (ES to GS)	0.16×10^{-12}	s
τ_{12}	Carrier escape time (GS to ES)	1.2×10^{-12}	s
τ_{1R}	Spontaneous radiative lifetime in GS	0.4×10^{-9}	s
I	Injection current	3×10^{-3}	A

where P_A and P_B are the powers of the input signals.

In the proposed AND gate, the output signal from the power combiner is the input signal to the OHL, that is, $P_{in} = P_{PC}$. Therefore, the output signal power of the proposed all-optical AND gate, P_{AND}, is expressed as:

$$P_{AND} = \frac{P_A + P_B + 2\sqrt{P_A P_B}}{8} \times \left\{ G_1 + G_2 + 2\sqrt{G_1 G_2} \cos(\Delta\phi + \phi_1 - \phi_2) \right\} \quad (8)$$

4. Results and Discussion

The parameters used for the QD-SOA in the numerical analysis are shown in Table 2. The value of the phase shift in the PS is $\Delta\phi = -29°$ [5]. The input signals with a wavelength of 1550nm are modeled by RZ bit sequence at bit rates 120 to 960 Gbit/s with Gaussian shape and full width at half maximum (FWHM) of 25% with an intensity of −2 dBm. The system operating environment is ideal.

To numerically assess the performance of the AND gate, one appropriate metric is the extinction ratio (ER). The ER is defined as:

$$ER(dB) = 10 \log \frac{P^1_{\min}}{P^0_{\max}} \quad (9)$$

where $P^1_{\min}$ and $P^0_{\max}$ are the minimum and maximum values of the peak power, "1" state and "0" state, respectively. In this paper, an ER above 6 dB is considered as a sufficient value for detection of the signal [7].

In Fig. 4, we show the input waveforms of signal A, signal B and the output signal waveform when the bit rate is 120 Gbit/s. It is found that the output light intensity is high only if each light intensity of input signals A and B is high. This result agrees with the values in Table 1.

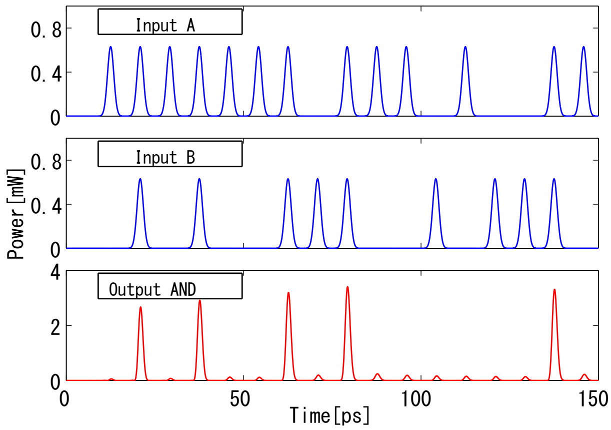

Fig. 4: Input and output waveforms for all-optical AND gate

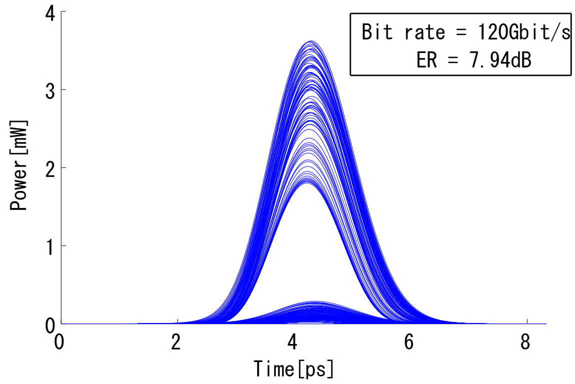

Fig. 5: Eye diagram for 120 Gbit/s bit rate

Figs. 5, 6 and 7 show eye diagrams for the output signal of the AND gate when the bit rates are 120, 600 and 960 Gbit/s, respectively. When a bit rate is 120 Gbit/s, the eye opening can be seen clearly. Here, we obtain ER = 7.94 dB. It is also shown that this ER is sufficient to operate as a logic gate. When a bit rate is 600 Gbit/s, we obtain ER = 7.13 dB, nevertheless, the bit rate is increasing. The eye is still sufficiently open. However, at a bit rate of 960 Gbit/s, the eye is not sufficiently open due to the pattern effect, and we only obtain ER = 5.80 dB, which is unsatisfactory (not over 6 dB).

Fig. 8 shows ER versus bit rate. This result shows that ER decreases as the bit rate increases. This reason is that the output light of QD-SOA can not be amplified sufficiently due to the increasing of the bit rate. However, the AND gate can achieve a sufficient ER (over 6 dB) for a bit rate which is less than or equal to 840 Gbit/s.

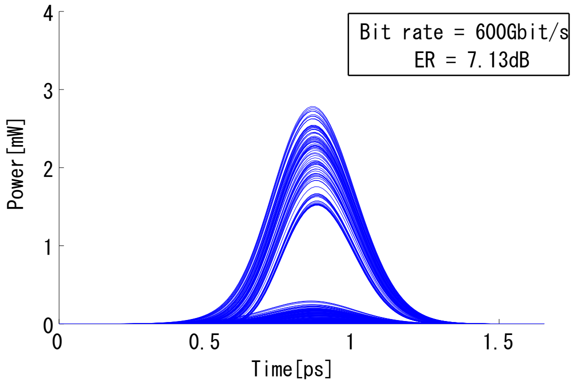

Fig. 6: Eye diagram for 600 Gbit/s bit rate

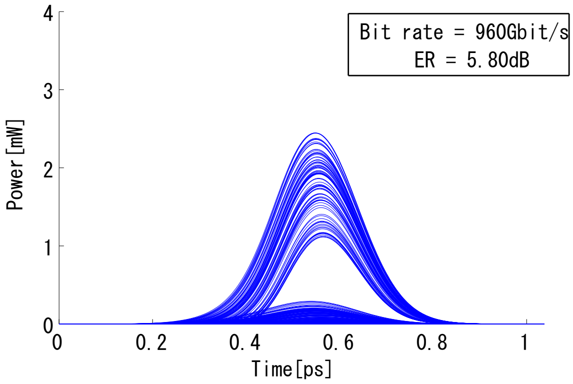

Fig. 7: Eye diagram for 960 Gbit/s bit rate

5. Conclusion

In this paper, we have proposed an all-optical AND gate using an OHL. The OHL is based on an MZI with a QD-SOA and utilizes SPM. We evaluate the performance of the AND gate using numerical analysis, and present input-output waveforms and eye diagrams. It is found that a sufficiently high ER (over 6 dB) can be obtained for bit rates of up to 840 Gbit/s.

Acknowledgments

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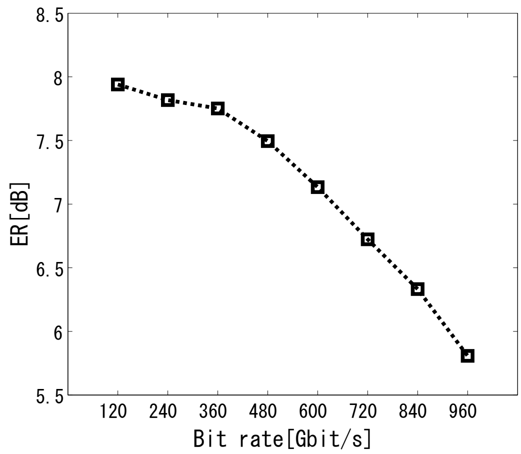

Fig. 8: ER versus bit rate

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